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DEPLOYMENT SIMULATIONS OF A FOLD-UP SYNTHETIC APERTURE RADAR ARRAY

B.C. Lopez, M.C. Lou*, E. Gama

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Abstract

Ground deployment testing and modeling for carpenter tape hinges (tape hinges) as deployment and latching devices for space applications are discussed. Due to their reliability and versatility, tape hinges have gained increased popularity in the aerospace industry. Successful correlation between a simulation and the ground deployment test of a panel array using these hinges, is presented here. This provides confidence in prediction of on-orbit deployment. As a reference for preliminary hinge design, parametric studies are also presented.

Introduction

Tape hinges are recommended[1] as an inexpensive and reliable device that is both a deployment and a latching mechanism, as part of a NASA effort to develop enabling technologies for the next generation of space synthetic aperture radars (SAR's). The use of this type of hinge requires high confidence in its performance and in a methodology to adequately predict on-orbit behavior.

One wing of the SAR array (6 panels) is considered here. The array is folded up in its stowed configuration and subsequently released. The hinge then "seeks" its most stable state (the latched condition), converting the stored strain-energy into kinetic energy in the process, until full deployment of the array is attained (See Fig. 1 for schematic of deployed SAR array). Although the on-orbit deployment process is driven by a simple exchange of energy, validation of a prediction methodology requires the rather challenging correlation to a ground deployment test.

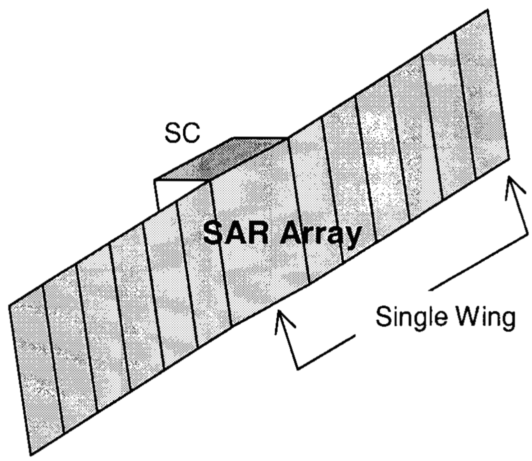

Figure 1 – Schematic of Spacecraft and SAR Array

* Associate Fellow AIAA

Ground Deployment Correlation

Correlation of the simulation and ground deployment test is conducted, to demonstrate predictability of on-orbit array behavior. And to show tape hinges can be used effectively as deployment and latching devices in a panel array as that proposed for the SAR.

The rationale used to show in-space behavior predictability is, that a ground-based deployment test is significantly more difficult to predict than an on-orbit deployment. This, due to challenges posed by gravity loads; hence, a successful correlation of a ground based deployment and its corresponding simulation provides confidence in the methodology for a simulation of on-orbit deployment.

Successful correlation is attained if the following conditions are met:

1. The simulation model is physically equivalent to the real structure and its mechanisms (mass properties, energy sources, energy losses, boundary conditions, etc.), with justifiable assumptions or simplifications.
2. The deployment simulation shows a panel deployment history that is of similar characteristics as that of the real test.
3. Total or intermediate deployment times in the simulation, are in the same order of magnitude as that of the real ground test, with justifiable significant deviations, if any.

The simulation was conducted using Pro/MECHANICA Motion (Release 17.0). An array of 6 panels was considered; each panel has the following mass properties:

Weight: 7.0 lbs
Moments of Inertia (weight units):
$Ixx = 12{,}000\ lb{*}in^2$
$Iyy = 936\ lb{*}in^2$
$Izz = 12{,}900\ lb{*}in^2$
Center of Gravity: (0.002, 0, -0.32) in
Overall Length = 118.4 in
Overall Width = 28.07 in

The reference coordinate system is located at the geometric centroid of the panel, with the x-axis in the longitudinal direction and the z-axis perpendicular to the plane of the panel.

The following sequence shows intermediate and final deployment comparisons between the simulation and the actual test.

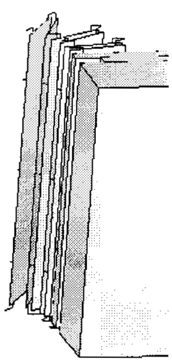

Fig. 2a. Time= 1.6 sec

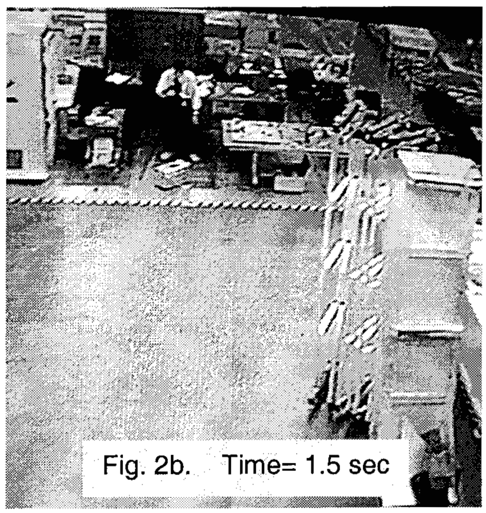

Fig. 2b. Time= 1.5 sec

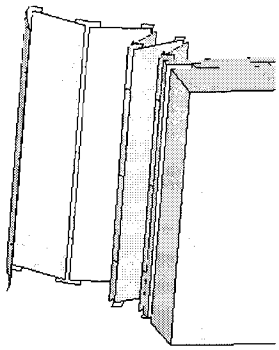

Fig. 3a. Time = 3.1 sec

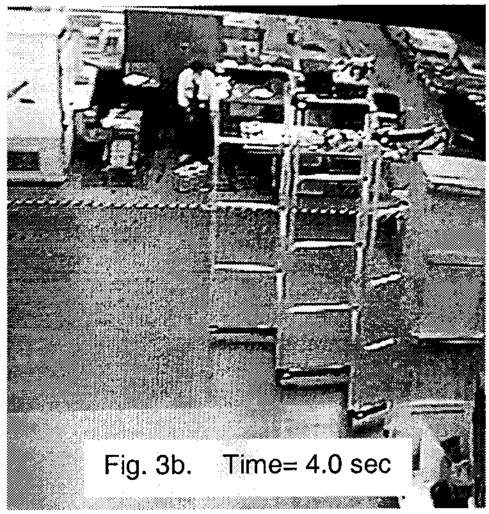

Fig. 3b. Time= 4.0 sec

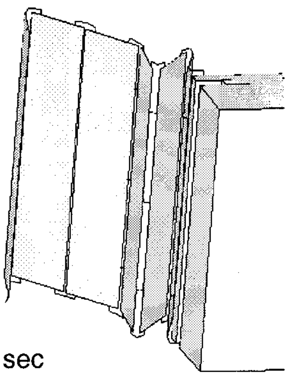

Fig. 4a. Time = 3.7 sec

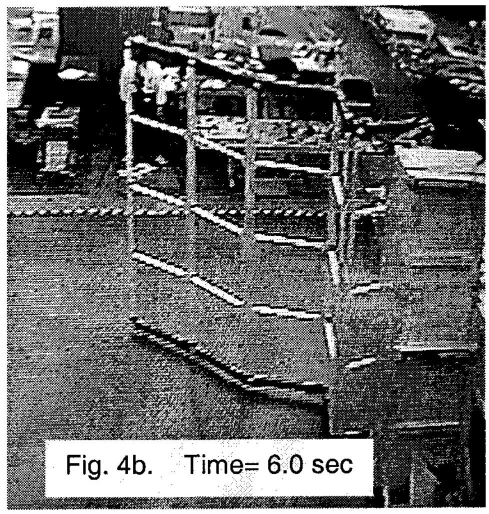

Fig. 4b. Time= 6.0 sec

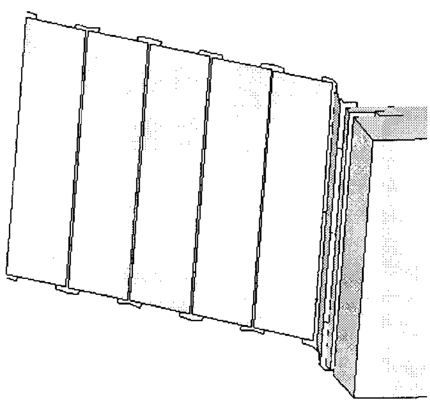

Fig. 5a. Time =6.7 sec

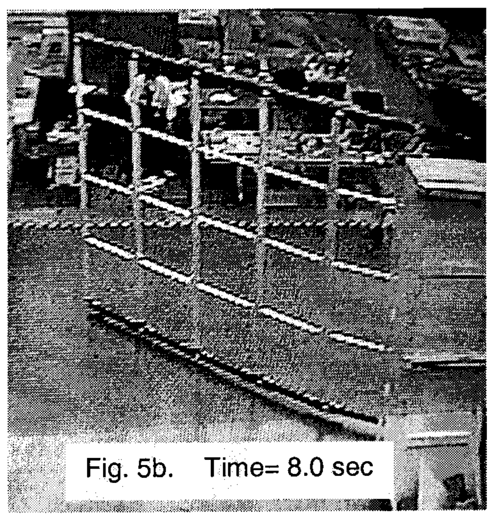

Fig. 5b. Time= 8.0 sec

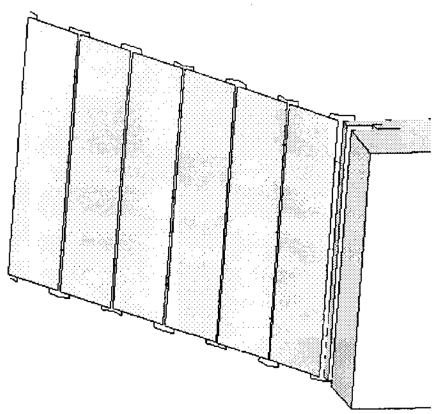

Fig. 6a. Time = 8.6 sec

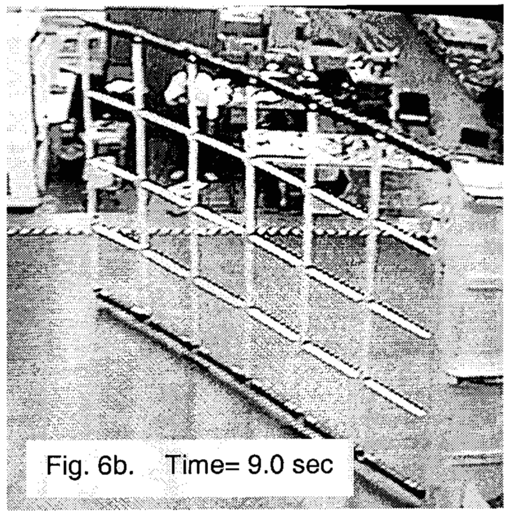

Fig. 6b. Time= 9.0 sec

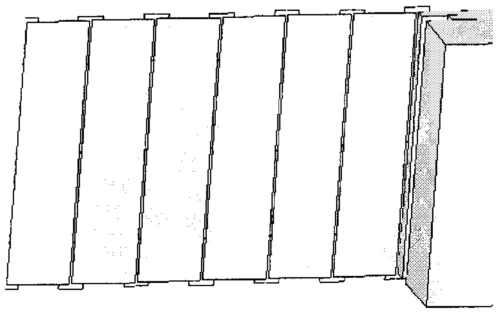

Fig. 7a. Time = 27 sec

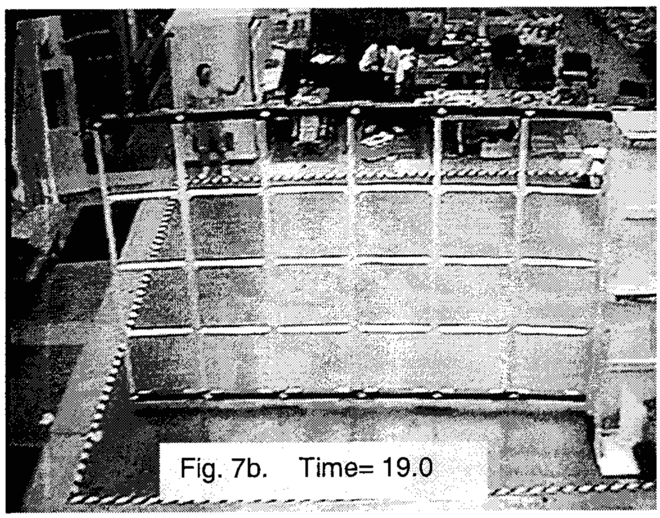

Fig. 7b. Time= 19.0

Simulation and test results show a very similar deployment history of all 6 panels. Total deployment time is predicted at 27 seconds versus19 seconds for the ground test.

This correlation satisfies the criteria discussed above, thus providing confidence in the methodology for prediction on on-orbit deployments using tape hinges.

Description of Tape Hinges

Tape hinges have been in use for many years now, but have recently gained popularity for various space applications. This is due to their reliability since they lack moving joints, and their versatility since they act as both deployment (the buckled regime) and latching devices (the unbuckled regime). This section describes in some detail hinge design and performance characteristics.

Figure 8 below shows a sample tape hinge used in the deployment test. The tape is commercial grade, made of 1095 cold rolled steel, width of 1 inch, and blade thickness of 5 mils. The paint on the tape has been tested for space compatibility and meets NASA JSC SP-R-022A outgassing requirements.

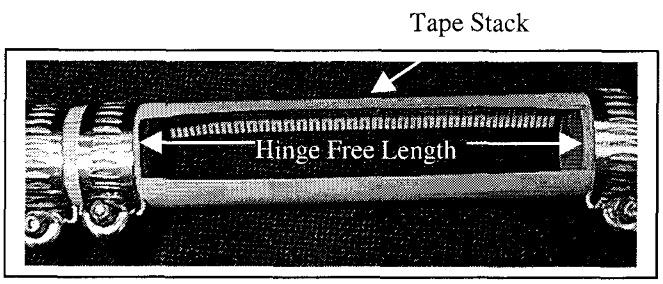

Figure 8 - Tape Hinge

Each hinge is comprised of two tape stacks with their concave side facing toward the hinge longitudinal axis. Each of the stacks may have one to four layers of tape (the term "number of layers" refers to the number of tape layers per stack).

The array features a four layer hinge at the root, three layer hinges at the other hinge-lines.

Tape hinges have two distinct performance regimes: When buckled, they exhibit non-linear behavior, with the ability to store significant amounts of energy in the tape deformations, which is released upon deployment; when latched, they act as a rather stiff composite beam (linear behavior).

Measuring Output Torque

Hinge output torque in the buckled regime is measurable by fixing one end of the hinge, placing a force gage at the free-end to record the hinge static force and measure the corresponding arm, at every angle of interest. See Fig. 9.

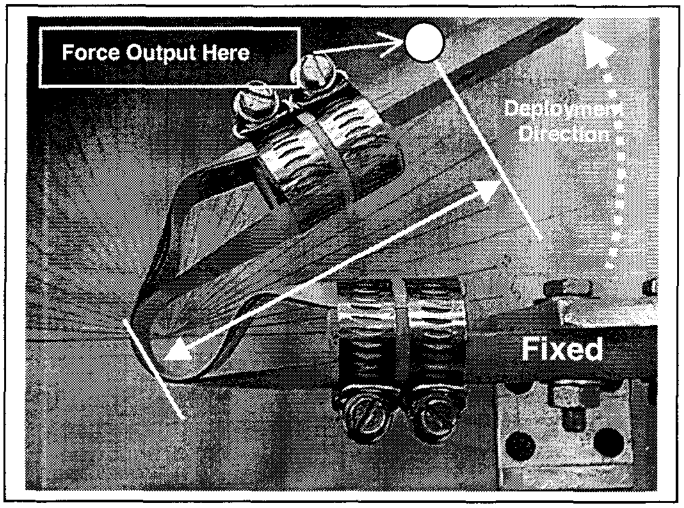

Figure 9 – Buckled Hinge and Torque Measurement

The loci of the torque output in the buckled regime, thus measured, comprise the regions labeled as "A" in Fig. 10 and bounded by "C". Region "B" corresponds to the hinge latched condition, the slope of the line is the bending stiffness of the hinge. The maxima labeled as "C" are the values for the hinge buckling moment; the associated buckling torque is an important value for the simulation.

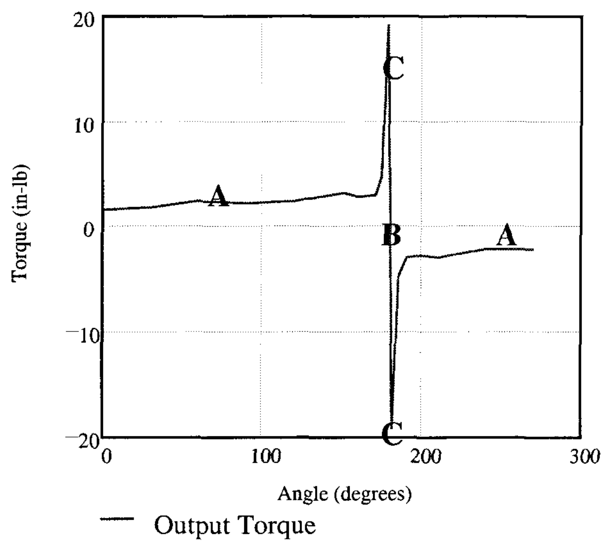

Figure 10 - Typical Hinge Torque Locus

This torque output profile sufficiently characterizes the kinetic and structural properties of the hinge to simulate deployment. Properties in the other degrees of freedom can be ignored if gravity effects are negligible or minimized.

Hinge Design Approach

For a space-borne application, the hinge design is driven by spacecraft requirements. In addition to these requirements, its design should respond to panel material properties and dimensions. Hinge and overall system mass properties determine total deployment time, deployment profile characteristics, final spacecraft tip-off or spin rate, and clearance margins.

Being that this case deals with a ground deployment, spacecraft requirements are not considered. To facilitate design issues, overall orderly and outward array deployment in 30 sec or less, were chosen as design requirements. An orderly deployment is described as the sequential extension or latching of panels 6-1. An outward deployment of the panels eliminates concerns of collision if two panel wings were simultaneouly deployed.

This section presents a practical hinge design methodology, with illustration of parametric studies that enable hinge design. The nominal hinge has a mean height of 0.8 in, a length of 4.0 in, and two tape layers per stack; these values apply for all hinges in the study, except as noted.

Hinge Height notably influences hinge torque output at the beginning and at the end of the deployment sequence. As shown by Fig. 11, hinge torque output tends to be higher for hinges of greater height in the regions between 0-30 degrees, as well as near its latched condition (180 degrees)

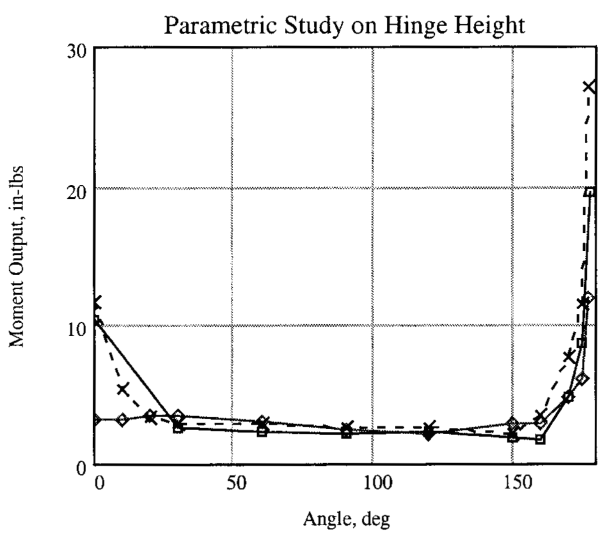

Figure 11

Similar to hinge height, the effect of **Hinge Length** is greater at low and at high deployment angles. However, at low angles and near the latched condition, torque output tends to be greater for shorter hinges. See Fig. 12.

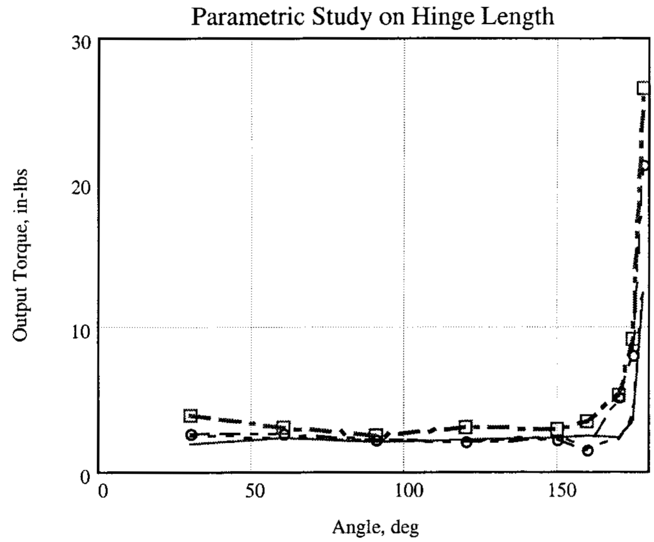

Figure 12

The **Number of Tape Layers** in a stack has greater overall impact in hinge performance, as shown in Fig. 13. It is a good practice not to exceed 4 layers.

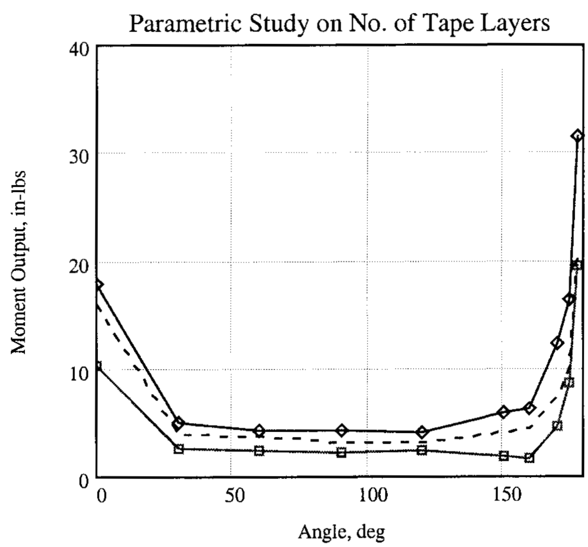

Figure 13

Within the buckled region, hinge torque output between 30 and 150 degrees does not vary greatly, average values are around 2.3 in-lb for a double layer hinge, 3.6 for a triple layer, and 4.72 in-lb for a quad layer hinge. A linear relation between torque output values and number of tapes per hinge stack emerges upon comparison of these values, at 1.2 in-lb per tape layer.

The parametric trends presented above provide an overview of the design issues of the hinge, in the buckled regime. The parameters discussed above also have an impact on the hinge performance in its unbuckled or linear regime. The following discussion provides a basis for a quick and rather accurate determination of latched-hinge bending stiffness.

The Latched Hinge. Characterization of the hinge as a latching device requires knowledge of two important quantities: The angle at which the latched hinge buckles and the buckling torque or critical moment. Experimental determination of hinge buckling angle is elusive at best. This angle can be found as the ratio of the buckling torque to the hinge stiffness. A NASTRAN linear buckling analysis calculates the critical moment, while a simple static analysis gives the hinge stiffness.

A quick way of determining the buckling moment for any hinge design, is by using the buckling load equation for clamped-free boundary conditions:

$$\mathrm{Pcrit}(E,I,L) := \frac{\pi^2}{4}\cdot\left(\frac{E\cdot I}{L^2}\right) \tag{1}$$

Where P_{crit} is the critical load under which a single tape leaf will buckle, E has a value of $3x10^7$ psi (Modulus for steel), I (area moment of inertia for a leaf) is $9.3x10^{-6}$ in^4, and L is the hinge free length. So, the buckling moment is found by the relation:

$$\mathrm{Mcrit}(N,E,I,L,H) := N\cdot \mathrm{Pcrit}(E,I,L)\cdot(H - 2\cdot 0.054) \tag{2}$$

Where N is the number of tape leaves or layers per stack, H is the hinge height, and the value 0.054 is the distance in inches between the leaf neutral axis to its apex (illustrated by Fig. 14).

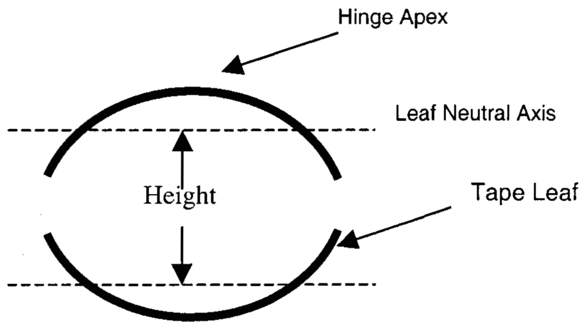

Figure 14 – Cross Sectional View of a Hinge

Buckling moments calculated this way, are typically 30% above NASTRAN predictions. But they have been correlated acceptably well (within 80%) with test data. While the equation is a fast way of determining buckling moment for any hinge configuration.

Description of Test Setup

The array deployment discussed here used a test fixture (See Fig. 15) comprised of a swing bar fitted with a rail, over which low friction wheels slide as the panels deploy. The wheels follow the deployment of panels 2, 4, and 6 via a bungee chord that connects a ring supporting the wheels to the panel below. Thus, the panels are suspended from the swing bar, through a slider mechanism.

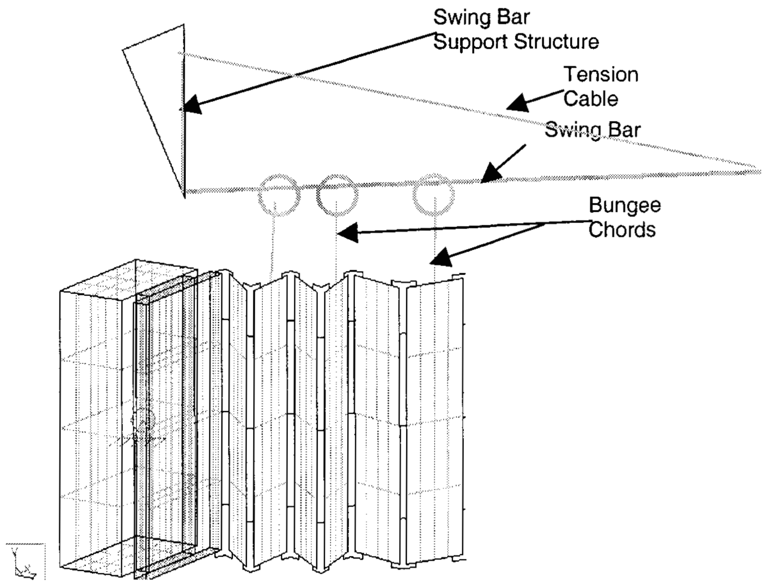

Figure 15 - Schematic of Test Set Up

The swing bar is attached to a vertical shaft in support structure; thrust bearings allow the bar to swing during panel deployment. Quasi-static beam deflection of the swing bar is minimized with the use of a tension cable.

Simulation Software Validation

In order to validate software capabilities, a couple of studies were conducted.

A single sample panel deployment using tape hinges was simulated and correlated to experimental deployment history. Figure 16 compares simulation deployment history to that determined experimentally. The correlation is very high.

Similarly, a deployment including frictional forces associated with a ground deployment was successfully correlated (Fig. 17).

This gives confidence in the software capabilities to adequately represent the physical characteristics of panel deployment.

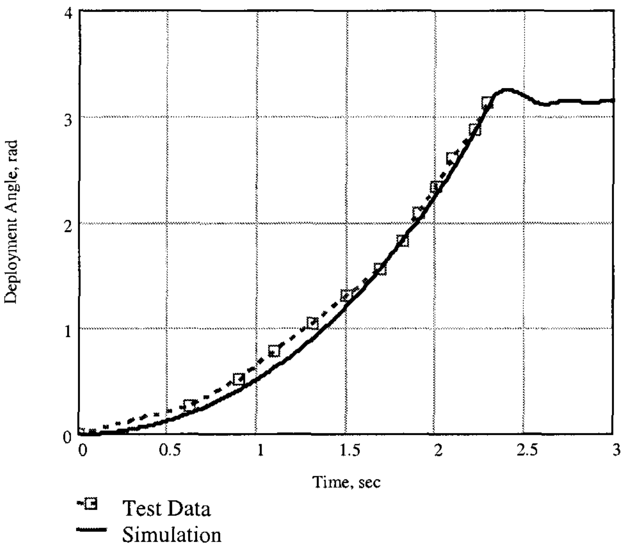

Figure 16 - Correlation of Single Panel Deployment

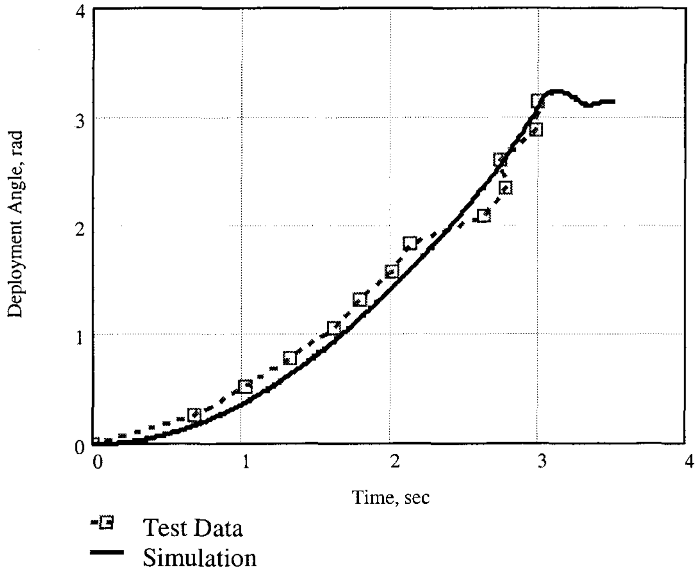

Figure 17 - Correlation of Single Panel Deployment (Including Friction Due to Gravity Off-loading)

Conclusions

The successful correlation of the simulation to actual panel deployment test, discussed here is a contribution to increase confidence in the predictability of on-orbit behavior of similar panel arrays using tape hinges as deployment and latching devices.

The hinge design overview has shown a practical and fast way to arrive at a hinge preliminary design.

Future work may concentrate on a more detailed characterization of hinge behavior as a function of parameter such as length, height, and number of layers.

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References

[1] Feria, V.A.; Lou, M.C.; Huang, J. and Speer, S.E. "Lightweight Deployable Space Radar Arrays" AIAA-98-1933.